Compact Tunable Terahertz Source based on Spintronic Magnon Lasing Effect

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***Abstract*— This paper presents a novel chip scale terahertz source based on spintronic magnon lasing effect for generating narrow band terahertz radiation tunable over a wide frequency range. The device is fabricated using industry standard semiconductor tools and methods employed for magnetic memory (MRAM).**

Keywords—terahertz; spintronics; magnon; laser; tunable; room temperature.

I. Motivation

Terahertz radiation is an attractive method for use in applications such as imaging, spectroscopy, and communications due to its unique ability to penetrate conventionally opaque materials, high chemical selectivity and non-ionizing safety profile. However, a main challenge in realizing the full potential of terahertz applications is the lack of availability of a compact, affordable, broadly tunable terahertz source.

Existing commercial terahertz sources are primarily based on femtosecond lasers, quantum cascade lasers (QCL) and to a smaller degree photo mixed diodes. While they can offer up to several milliwatts of output, these sources are physically large, complex, very expensive, limited mechanical tunability and/or are only available over a fairly narrow frequency range, typically below 4 THz.

Herein, we describe a novel chip-scale room temperature terahertz laser to provide tunable, narrowband emission of radiation over a wide frequency range from 1 to 30 GHz (Fig. 1). This approach is a radical departure from any terahertz source, by exploiting a novel spintronic magnon lasing effect [1].

II. Terahertz Magnon Laser Concept

The scientific foundation of the magnon laser was previously reported in *Physics Letters A* by Magtera's scientific founders Prof. Korenblit and Dr. Tankhilevich [2]. The essence of this approach relies on the new quantum mechanical effect - the Magnon Lasing Effect.

Magnon lasing can be implemented in ferromagnets with an exchange gap, Δ, in the electron spectrum. This effect involves injection of minority spin electrons from a spin-injector, through a magnetic tunnel junction barrier layer (MTJ) and into an active ferromagnetic (FM) layer. In the process, non-equilibrium magnons are generated that have energy in the terahertz region, and their subsequent merging leads to production of terahertz photon emission [1, 3].

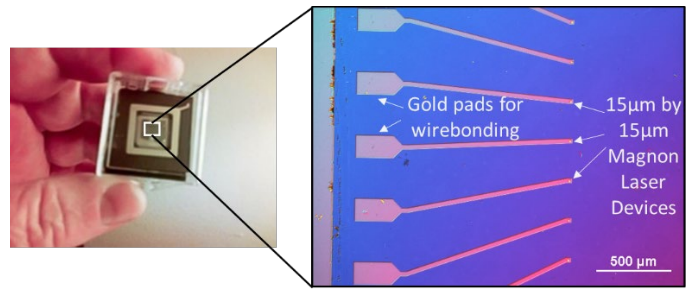

Fig. 1. Photo of Magtera terahertz magnon laser showing its compact, chip scale size. The device consists of an array of individual 15 μm x 15 μm micro-column magnon lasers.

Fig. 2 depicts the basic device architecture of a single magnon laser structure. The laser operates at room temperature and the output can be uniquely tuned over a large spectral range by controlling the applied voltage across the device. Furthermore, the laser is fabricated using industry standard semiconductor tools and methods used for standard Magnetic Random-Access Memory (MRAM) technology, thus enabling low cost, high volume capable production.

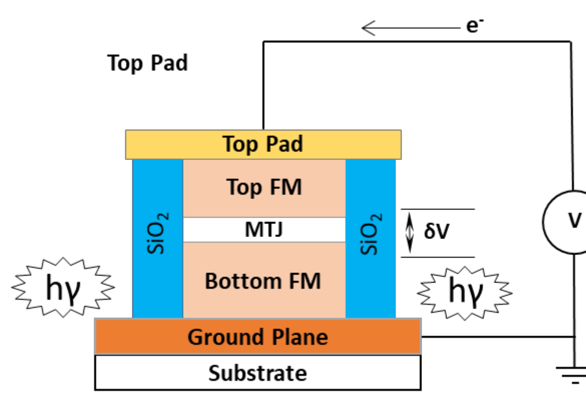

Fig. 2. Basic device architecture of a single magnon laser column pillar.

III. PHYSCIS OF TERAHERTZ MAGNON LASER

The underlying principle of terahertz emission occurs from the generation and merging of non-equilibrium magnons (Fig. 3). A magnon is a collective excitation of the electrons' spin structure in a crystal lattice. In the equivalent wave picture of quantum mechanics, a magnon can be viewed as a quantized spin wave. As a quasiparticle, a magnon carries a fixed amount of energy and lattice momentum. It also possesses a spin of ħ (where ħ is the reduced Planck constant).

The Top FM (spin injector) is set to have magnetization oriented antiparallel in relationship to the magnetization of the Bottom FM active layer that includes Magnon Gain Medium. Minority electrons with spin down are injected from the Top FM (spin injector) to upper sub-band of the Bottom FM when a voltage is applied to the device and the Fermi level, E_{F2}, of the Top FM (spin injector) is lifted to the bottom level of the upper sub-band of the Bottom FM. The injected minority electrons are tunneling via the tunnel junction and this tunneling process is instantaneous.

After injection, the minority electron (with spin down) will then rapidly flip spin by passing into the high energy excited state in the sub-band with spin up by emitting a non-equilibrium magnon, at a time scale of $\sim 10^{-13}$ sec. At this point, the electron will scatter on equilibrium electrons on the time scale of 10^{-14} sec. Thus, the electron cannot return into the upper sub-band as it will need more time to absorb magnon than to scatter on equilibrium electrons with spin up, thus initiating a magnon lasing process. Two such non-equilibrium magnons will merge producing a photon on the time scale of 10^{-7} sec, with very narrow MHz linewidth.

The non-equilibrium magnon has a wave vector $q = \hbar^{-1} (2m\Delta)^{1/2}$, where m is the effective electron mass. The energy of the excited magnon is $\hbar\omega = Dq^2$, where D is the spin wave stiffness, q is the magnon wave vector $\hbar^{-1} (2m\Delta)^{1/2}$ and the frequency $f_m = (2\pi)^{-1}\omega$. In ferromagnetic materials, Δ is the distance between the majority and minority sub-bands with typical values of 0.6 eV [4]. The stiffness D is in the range of 400 to 500 meV-A^2 [5] and m can be approximated between 1.1 to 1.7 m_o where m_o is the free electron mass [6]. Using these estimates, the maximum frequency of the magnon is on the order of 10 to 15 terahertz and the peak frequency (f_{max}) of THz radiation is between 20 to 30 THz accordingly, as it was created by merging of two non-equilibrium magnons. Once a critical pumping rate is reached, the generation of magnons begins to avalanche and the system lazes.

IV. VOLTAGE-BASED FREQUENCY TUNABILITY

The Magnon Terahertz Laser is different than a conventional optical laser, as it does not have an external cavity. This is because magnons do not exist outside ferromagnetic materials and therefore are naturally contained within the laser structure. However, it is possible to tune the laser over a wide frequency range (down from the max frequency of about 30 THz to the minimum frequency of about 1 THz) by varying the bias voltage. The exact numbers depend on the half- metal used as Magnon Gain Medium.

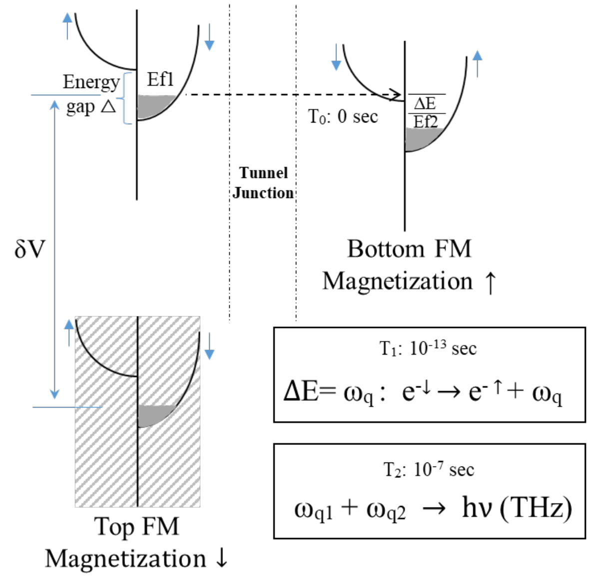

Fig. 3. The physics of magnon lazing. The Top FM (spin injector) magnetization is oriented antiparallel to the bottom FM active layer. When a voltage is applied, the Fermi level, E_{F2}, of the Top FM is lifted to the bottom level of the upper sub-band of the Bottom FM, results in injecting minority (spin-down) electrons. The minority electron then rapidly flip spin by passing into the high energy excited state in the sub-band by emitting a non-equilibrium magnon, at a time scale of $\sim 10^{-13}$ sec. Two such magnons will then merge into a photon on the time scale of 10^{-7} sec.

Voltage-based tunability is directly attributed to the tunneling properties of the tunnel junction and the physics of magnon lasing, as described above. An increase in bias voltage causes an increase in the maximum energy of the injected minority electrons. The electrons with maximum energy have the highest tunneling probability to flip spin, generate magnons and emit radiation. Thus, the lazing magnon frequency is determined the maximum energy of the injected minority electrons and therefore by the bias voltage. Once the lasing point is reached, a further increase to the voltage bias will increase the maximum energy and momenta of electrons with the highest tunneling probability thus causing the further decrease of the magnon lasing wave vector and correspondingly a decrease of terahertz frequency [3]. *The tuning of the lasing frequency is parametrically large because the ratio of the energy gap to the shift in bias is a large parameter*, meaning a small change in bias results in a large change in the electron energy and therefore in a large change in lasing frequency. As an example, the THz frequency can be adjusted between f_{max} and 0.9 f_{max} just by changing the tuning voltage by just 1%.

V. PRELIMINARY RESULTS

Preliminary magnon devices have been fabricated by Molecular Beam Epitaxy (MBE) for thin film deposition of the active magnetic and tunnel junction layers. A self-aligning process is then used to create arrays of vertical micro column stacks by etching a pillar past the tunneling barrier, deposition of passivation or isolation dielectric, and finally deposition of contact electrodes.

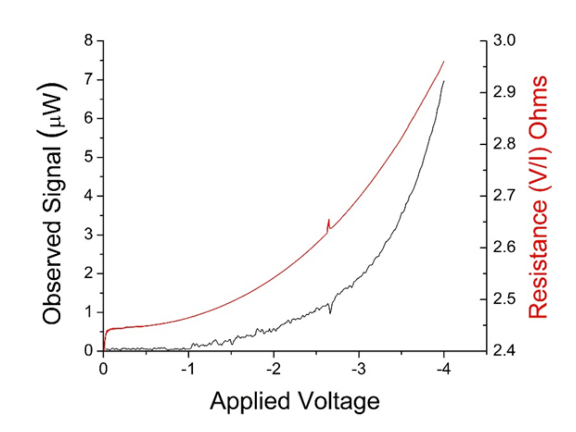

Fig. 4. Optical (black) and resistance (red) measurements as a function of voltage applied to the device. The small resistance feature at -3V is an instrumentation artifact.

Device performance is shown in Fig 4. The signal is measured from a single micro-column with dimensions of 15 μ by 15 μ, within a patterned array of 100 micro-columns. Voltage applied to the device was scanned from 0 to -4 volts. Observed optical power in μW (black) is shown at the left, while device resistance (red) is shown at right. Optical curves show exponential dependence of output power on applied voltage (Note, the optical signal has an onset threshold at approximately -1V.). The increase in device resistance with voltage is attributed to opening one more channel of relaxation for minority electrons by generating non-equilibrium magnons.

Optical detection was made using a Genetec radiometer and recorded the total emission from 1 to 30 terahertz. The total power output from a single multilayer column at -4V was about 23 μW. Thus, for an array of 100 micro-columns, the total output obtained would be 2.3 mW.

VI. Applications

A compact, low cost, broadly tunable terahertz source would enable new devices and systems for use in a range of fields including defense/security and communications.

A). Real time point detection of chemicals, explosives, and biological agents

Techniques such as mid-infrared (mid-IR) spectroscopy are commonly used to identify different materials and samples. At these frequencies, commonly 500 – 4,000 cm^{-1} (15 – 120 THz), as shown in Fig. 5, the mid-IR radiation probes the high energy, high frequency intramolecular bonds such as the functional group rotations, oscillations and stretches highlighted in Fig. 6a. The frequencies of these functional group vibrational modes are well known, and the ''fingerprint region'' between approximately 500 – 1,500 cm^{-1} gives a lot of information as to the chemical composition of the molecule (see Fig. 6b for an example mid-IR spectrum of malic acid).

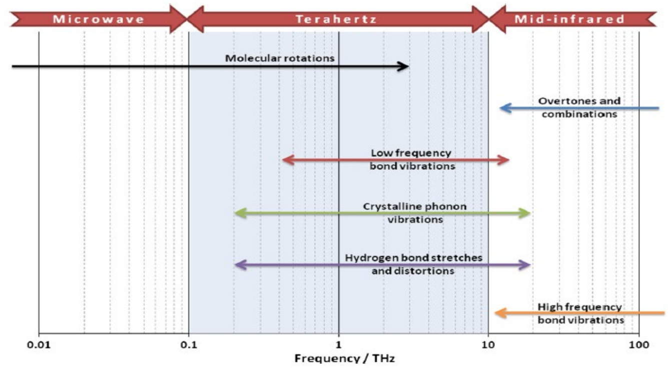

Fig. 5. Illustration of various molecular interactions in THz frequency region [7].

In contrast, terahertz frequency radiation 3.3 – 330 cm^{-1} (0.1 – 10 THz) is lower in energy, and so the characteristic length scale of the radiation is longer than for mid-IR radiation. As a consequence, terahertz frequency radiation probes the longer-range, lower energy intermolecular modes such as the hydrogen bond torsions and librations, (restricted rotations; that is, rocking motions) and whole molecule stretches, which are highlighted in Fig. 6c.

Magtera's tunable Terahertz Magnon laser would enable a compact system employing a chip scale THz source to generate and collect full terahertz spectra from 1 to 30 THz. Such a system would permit rapid identification of unique spectral characteristics of chemicals, explosives and biological agents.

B) Secure, high bandwidth THz communications

Terahertz presents a new frontier for communications with its extremely high bandwidth (terabits per second), high security and minimal risk to human health in short to medium range applications.

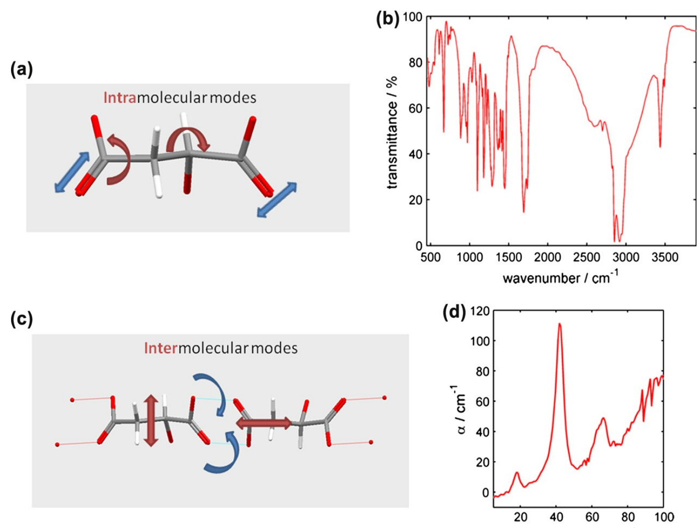

Fig. 6. Illustration of DL-malic acid molecule depicting representative types of (a) intramolecular and (c) intermolecular vibrational modes, and the corresponding (b) mid-infrared spectrum and (d) terahertz spectrum.

The basic architecture of secure short-range coherent terahertz communication system comprises a Terahertz Magnon Laser in a coherent implementation; a modulator block; a transmitting THz antenna; a THz receiver comprising a THz receiving antenna; a Schottky mixer block [8]; a demodulator, and a digital block.

Secure communication is enabled due to the narrow divergence with the use of coherent THz laser beam provided by the magnon laser. Indeed, for a coherent signal, the beam size (w_z) along the direction of propagation (z) of the Gaussian beam is given by [9]

$$w_z = w_o \sqrt{1+ (\lambda z/\pi w_o^2)^2} \quad (1)$$

where w_o is the beam size at distance z=0, D is the aperture size, and λ is the wavelength.

For a coherent THz signal having 1 mW of transmitted power emanating from a 1 mm aperture, the divergence at a distance of 100 m is 1 m according to (1). A recipient would detect the signal with a power loss of only about 60 dB. In contrast, use of a non-coherent THz signal, the beam divergence would be hundred times greater (100 m) and the corresponding loss of energy at the receiver would be significantly larger (100 dB).

A THz communication system using the coherent Magnon Laser allows for a small footprint, high bandwidth and secure communications from narrow beam size.

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